Development and Fabrication of Prototype Undulator U15 for SwissFEL

Presenting author: Urs Ellenberger
Paul Scherrer Institut, 5232 Villigen PSI, Switzerland
urs.ellenberger@psi.ch

Co-author(s): Thomas Schmidt, Marco Calvi, Pirmin Böhler, Andreas Keller, Marcel Locher, Arthur Imhof, Steffen Danner, Marc Bruegger, Haimo Joehri, Thomas Stapf, Johan Wickstroem, Peter Huber
Paul Scherrer Institut, 5232 Villigen PSI, Switzerland

Theme:
Stable and cost-efficient planar in-vacuum undulator U15 (15 mm magnetic period) and a gap of 4.3 mm in a generic O-shaped closed frame of cast mineral.

Abstract:

The first beamline Aramis of SwissFEL driven by the linac will be hard X-ray and covers the wavelength range of 1 to 7 Å. For Aramis a planar in-vacuum undulator with a nominal working gap of 4.3 mm and a magnetic period of 15 mm (U15) has been designed in-house. It is currently being built by an industrial partner as a full scale functional model. The goals are to test the high precision of the wedge drive system to better than 1 μm accuracy and of the mechanical design. Design concepts are presented and measurements performed so far look very promising. Without changing its design the frame of the undulator U15 will allow to carry other types of vacuum chambers and magnets. The fully functional prototype of the undulator U15 is expected to be completed and delievered to the institute by end of 2012 to start commissioning.

1-Overview

SwissFEL with electron energies of 5.8 GeV will have two undulator lines for hard- and soft x-rays [1]. The first beamline Aramis of SwissFEL to be commissioned in 2016 is driven by the linac to produce hard X-ray (1 to 7 A). For this purpose a planar and in-vacuum undulator with a short magnetic period of 15 mm (U15) and a variable gap between 3 mm to 19 mm (nominal working gap is 4.3 mm) has been designed in-house and is currently being built in industry.

Beamline	Design	magnetic period	Gap B-field	Gap-size	X-rays
Aramis (2016) undulator U15	Planar	15 mm	In-vacuum	4.3 mm nom. (3 – 19) mm	(7 – 1) Å (1.8 – 12.4) keV
Athos (2020) U40 and UE40	Planar, Apple II	40 mm	In-vacuum In-air		60 – 6) Å (0.2 – 2) keV

Table 1: Planned FEL lines with corresponding undulators U15, U40 and UE40.

A novel type of permanent magnet is used and mounted on arrays inside a vacuum tank to allow operation at room temperature. The magnetic material is NeFeB with diffusion of Dy along the grain boundaries for stabilization (Hitachi metal Ltd., [4]). The remanence is 1.25 T with a coercitivity higher than 2300 kA/m. Comparable parameters are otherwise only achieved with costly nitrogen cooling systems. A total of 12 undulators of this type U15, each 4m long, have to be built and to be aligned in a row within tight tolerances to ensure the SASE saturation regime for Aramis FEL in 2016 [2].

A cost optimized design from the start for all undulators of SwissFEL is mandatory. All components of the undulators have been designed in-house and are cost-optimized with industrial partners for a cost efficient series production. Therefore we use the following concepts to profit best from series production issues for undulators (U15, U40 and UE40):

- Design of an O-shaped closed frame is modular (suited for U15 and for other undulators of SwissFEL), stable (cast mineral) and cost efficient.
- Use of cast (base plate of frame contains all tubes necessary for cabling) and extruded materials (i.E. outer I-beam, keeper block to hold magnets) and an optimized design is best for low-cost industrial series production.
- Reduced engineering (use of same and optimized design concepts)
- Same 5-axis CAM shaft movers for the feet of the cast mineral frames (Designed at SLAC and already used for SLS girders and undulators.)
- Same transport concept with containment and air-cushions
- Same material to be supplied (besides vacuum chambers and magnets)

2-Goals and specific requirements of undulator U15

The basic design goals of the SwissFEL undulators are summarized below [3]:

- Short period undulator (U15) for Aramis beamline
- Variable polarization (U40 and UE40) for Athos beamline
- Low beam height (1.2 m from floor)
- A rigid O-shaped frame of cast mineral transfers its high stiffness through outer and inner I-beams to the magnets where it is required
- Precise gap drive system (mounted on undulator)
- Remote controlled alignment of an undulator (5-axis CAM shaft movers)

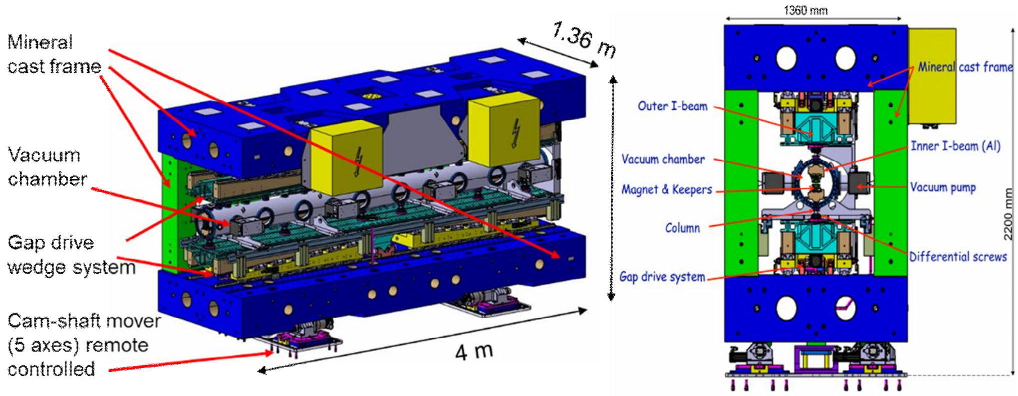


Fig. 1: Side view and cross section of undulator U15 of SwissFEL

The magnetic period of the undulator becomes smaller the lower the electron energy of the FEL is to achieve X-rays of 1 Å. For a SwissFEL energy of 5.8 GeV and a magnetic period of the undulator of 15 mm we have found a linear relationship between SwissFEL and other existing FEL sources. SwissFEL represents a data point at the lower end and one can speculate whether the curve (fig. 2) may be extrapolated to even smaller FEL energies and corresponding magnetic periods of undulators for X-rays of 1 Å. The key parameters of the undulator U15 are summarized in table 2.

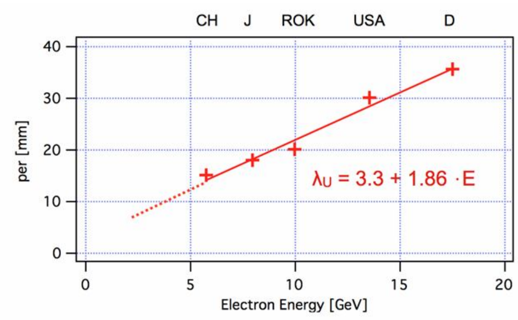


Fig. 2: Linear relationship between electron energy and magnetic period

Aramis Undulator Hybrid – In vacuum	
Undulator length	3990 mm
period	15 mm
Number of undulators	12
Number of period segments	266
Nominal K value	1.8 – 1.0
Nominal gap range (20 mm for open gap)	3.2 – 5.5 mm
Pole magnetic field Bz on axis	1.27 – 0.7 T

Tab. 2: Key parameters of U15 undulator

3-Key components of design of undulator U15

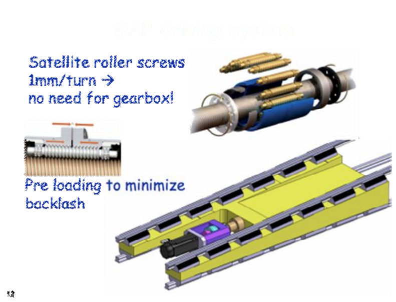
Important factors for the proper functionality of the undulator U15 are [3]:

- Precision of the gap setting
- Gap change due to outer I-beam because of machining precision
- Stiffness of outer and inner I-beam under magnetic load (equal to 2.7 tons)

Gap drive system (precision and accuracy)

To guide the stiffness of the cast mineral frame to the outer I-beam a wedge-based drive system of high stiffness and precision has been designed. A pair of two wedges is moved synchronously against each other to lift-up and down the outer I-beam. The outer I-beam is made of extruded aluminum and couples mechanically two wedges of each pair. For small gaps the wedges move out to minimize mechanical deflection of outer I-beams.

The gap drive system uses servo motors (Beckhoff) to drive satellite roller screws from Rollvis (Swiss) with a pitch of 1mm only to adjust the wedges. Together with a further reduction of 1:10 by 3° wedge angles a gearbox-free drive system with a minimized backslash (0.3 µm) has been realized. The drive system is integrated in small cabinets attached to the undulator [3].



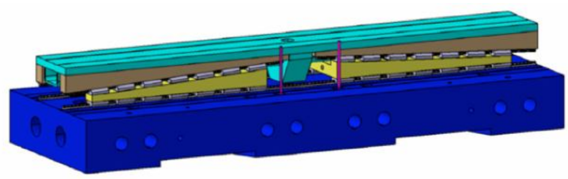


Fig. 3: Gap-drive system with satellite roller screws from Rollvis (left) to adjust wedges to drive the outer I-beam.

The U15 undulator has a gap range from 3 to 18 mm. For highest precision the aluminum wedges and their counterpieces are grinded in one clamping. Each wedge is connected to the mineral base and its counterpiece by 4x7 preloaded bearings. The I-beam itself is laterally fixed in the center by a massive bearing which is glued into the cast mineral base. This bearing is required because of the longitudinal forces of the APPLE II type UE40 undulator.

At each end of the wedges is an absolute linear encoder (Heidenhain). The minimum step-width of the gap is about 0.2 µm. The gap variation for gaps of 3 to 6 mm has been measured with an interferometer and compared to encoder settings. The difference between laser interferometer measurements and encoder reading is +/- 1 µm (accuracy of gap drive system). The reproducibility of the measurements is +/- 0.5 µm. This has been checked by variation of gap settings around 4.4 mm (nominal and optimized for U15) with the laser interferometer.

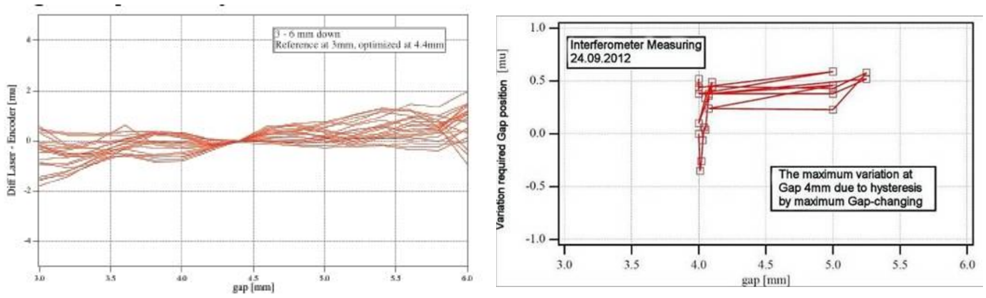


Fig. 4: Accuracy of gap drive system is +/- 2 µm (left, optimized at 4.4 mm) with a reproducibility of a repeated gap setting of +/- 0.5 µm (right).

Outer I-beams (flatness)

The outer I-beams have precise machined surfaces of < 10 µm along 4 m. This flatness has been verified with an electronic inclinometer (Wyler Blue Level) with an accuracy of 1 µm/m when the outer I-beams were on the floor.

To guarantee a homogenous gap variation all along the 4m long undulator parallelism of the two outer I-beams has to be checked after assembly of the top frame (only weight force, no magnetic forces). The parallelism has been measured on 2 traces (3 mm apart) between upper and lower I-beam.

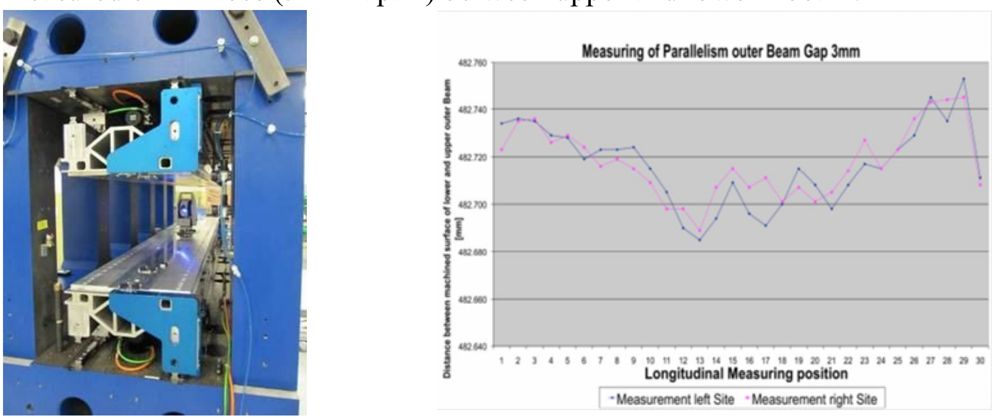
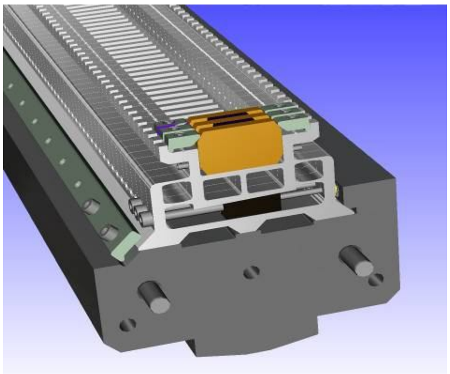


Fig. 5: Setup with laser tracker (left) to measure parallelism between upper and lower I-beams mounted in frame which is < 50 µm (< 10 µm on one side).

This has been performed with a laser tracker (accurate to 10 μm) and with the inclinometer (accurate to 1 μm) for cross-checking. The two traces on the bottom I-beam (3mm apart on the precise machined reference surface) do vary within 10 μm with respect to each other and within 50 μm referring to the pair of traces of the upper I-beam.

Block keepers of inner I-beams to hold the magnets

The U15 undulator has a hybrid magnetic structure made out of permanent magnets (NdFeB-Dy, 4.1 mm thick, TiN coated) and of iron (permendur) poles (CoFeV). The configuration is one single pole and one single magnet as the building block of the magnetic structure [4]. The magnets and poles are arranged into block keepers. They are made of extruded aluminum and consist of 22 periods of a pair of one magnet and one pole. The height of poles and magnets can be adjusted individually with a system of screws, wedges and weak-link elements (or flexors) in the range of +/- 20 μm with a submicrometer precision for shimming of the magnets. The screw mechanism also allows an automated procedure with a robot arm that drives each screw to correct for B-field deviation after hall-probe masurements (see further below).



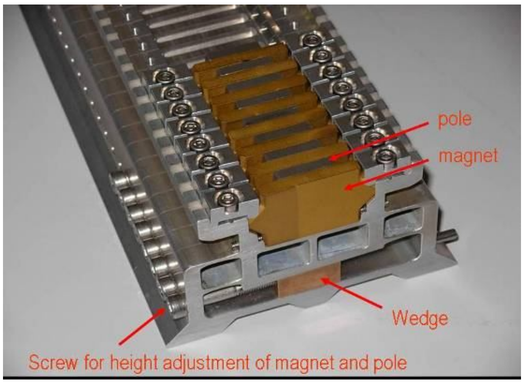


Fig. 6: Design of block-keeper unit (left) and as manufactured (right)

Micro undulator and first test results

In order to test the magnetic structure (magnets, poles and block keepers) they are mounted on inner I-beams in a short stiff frame (referred to as “microundulator”) where 2 block keepers or 44 periods of magnets and poles are facing each other. The windows on the two sides give access to the hall probe measuring head [4].

First test measurements are performed before any optimization. First K-values are calculated from magnetic field measurements and gap settings using the code RADIA. The agreement between simulations and measurements of K-values versus gap-settings is very good as expected (i.E. K = 1.2 for gap = 4.4 mm). There is no evidence of magnet demagnetization caused eventually by the assembly procedure of magnets and poles. The trajectories for gaps between 2.7 to 6.0 mm with unsorted magnets have been calculated for 5.8 GeV electrons and they look very promising (i.E. horizontal trajectories are within 2 μm) [4].

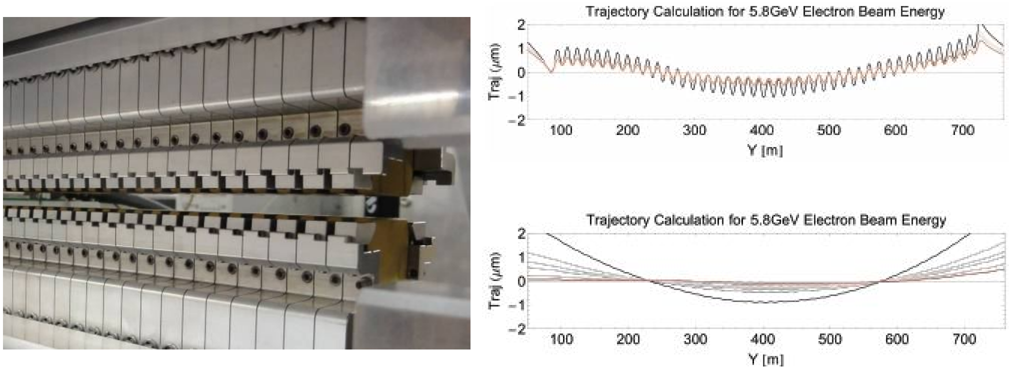


Fig. 7: Window for hall probe between magnetic structures of microundulator (left) and calculated trajectories (right) from B-field measurements.

Integrated and automated system for magnet adjustments

Because of the closed frame of the undulator we have designed an automated measuring (B-field variations) and adjusting (magnet and pole heights) system. It consists of the hall probe setup followed by an one-axis robot with a screw driver both running on the same probe bench and driven by a linear motor. The same system will be integrated into an in-air (UE40, Apple II) as well as into an in-vacuum undulator (U-15, U-40).

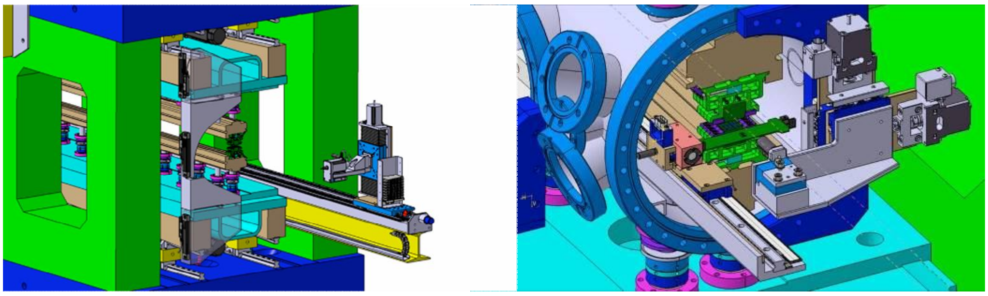


Fig. 8: Hall-probe measurement benches for magnet optimization (left) and absolute field measurements after installation of the vacuum tank (right).

4-Status and outlook

The prototype undulator U-15 has been assembled, tested and measured (within specifications) at MDC (Max Daetwyler Company, Switzerland). After delivery to PSI by end of 2012 and optimization of the magnetic structures the undulator U-15 will be built in the 250 MeV-injector in September 2013.

References

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[2] R. Ganter et al., Technical Overview of the SwissFEL Undulator Line, Proceedings FEL Conference (2012)

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